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Giant planet formation from disk instability; cooling and heating

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Abstract.

We present the results of high resolution SPH simulations of the evolution of gravitationally unstable protoplanetary disks. We report on calculations in which the disk is evolved using a locally isothermal or adiabatic equation of state (with shock heating), and also on new simulations in which cooling and heating by radiation are explicitly modeled. We find that disks with a minimum Toomre parameter < 1.4 fragment into several gravitationally bound protoplanets with masses from below to a few Jupiter masses. This is confirmed also in runs where the disk is given a quiet start, growing gradually in mass over several orbital times. A cooling time comparable to the orbital time is needed to achieve fragmentation, for disk masses in the range $0.08 - 0.1 M_{\odot}$. After about 30 orbital times, merging between the bound condensations always leads to 2-3 protoplanets on quite eccentric orbits.

The formation of gas giants as a result of fragmentation in a protoplanetary disk, an old idea (Kuiper 1951, Cameron 1978), has been recently revived by a number of studies that are finally laying the ground for a quantitative understanding of such process (Boss 2001, 2002; Mayer et al. 2002, 2003; Pickett et al. 2000, 2003). The renewed consideration of this mechanism stems from several problems faced by the conventional model of giant planet formation, in which first a rocky core is assembled over $10^5 - 10^6$ years and then a gaseous envelope is accreted in a few million years or more, the exact timescale being dependent on the details of the models like the disk surface density and the opacity of the mixture of gas and dust (Lissauer 1993). These timescales are an order of magnitude too long to form planets before the disk is dissipated by photoevaporation

in highly irradiated environments like the Orion nebula (Throop et al. 2001), and are a bit too tight even when compared to the typical lifetime of disks in more quiet environments like Taurus (Haisch, Lada & Lada 2001). One of the strong points of the core accretion model, namely the prediction that gas giants have solid cores, is considerably weakened now that new models of the interior of Jupiter are consistent with the total absence of such a core (Guillot 1999). The discovery of extrasolar planets (Marcy & Butler 1998) has worsened the situation further because now we need to explain the existence of very massive planets, up to ten times larger than Jupiter, that in the standard model would either take too long to be formed, might not form at all (Bate et al. 2003) or could migrate towards the central star before being able to accrete enough mass (Nelson et al. 2000). The distribution of their orbital eccentricities must also be explained; whilst in the past few years several papers have proposed a variety of explanations, sometimes tuned to the properties of one particular system, none of these is valid in general. Mayer et al. (2002, hereafter MA02) showed for the first time that if a massive disk remains cold long enough, until the growing overdensities reach some density threshold, fragmentation takes place even when heating from compression and shocks is included —the resulting clumps survive for tens of orbital times, leading to systems of only a few protoplanets with masses and orbital eccentricities in the range of observed extrasolar planets. The strong point of the 3D smoothed particle hydrodynamics (SPH) simulations of MA02 was the high resolution (up to 10^6 gas particles) that allowed to resolve the local Jeans length across a wide range of densities, including the regime in which fragmentation takes place (Bate & Burkert 1997; Nelson 2003). However, these simulations were quite simplified in the thermodynamics (see Pickett et al. 2000; 2003), since only two extreme conditions, a locally isothermal or an adiabatic equation of state (with shock heating), were employed. Boss (2001, 2002), by using radiative transfer in the diffusion approximation, has shown that efficient cooling in the disk midplane can occur thanks to convective transport of heat to the disk atmosphere. He finds that the timescale for convective cooling is comparable to the orbital time in the outer, colder regions of a disk of mass $\sim 0.1M_{\odot}$. Here we review the main results obtained with the large survey of simulations extensively described in Mayer et al. (2003, hereafter MA03), and we present the first results of new simulations in which radiative cooling and heating are directly implemented. Following recent work by Pickett et al. (2003) and Rice et al. (2003a,b), we will investigate how fast cooling has to be for fragmentation into gravitationally bound planets to occur.

1. Initial Conditions and Simulations

The 3D disk models initially extend between 4 and 20 AU. The central star is modeled as a softened point mass with a mass of $1M_{\odot}$. There are no fixed boundaries; the disk is free to expand and contract and both the central star and the disk can respond to their mutual gravitational field. The disk surface density profile is of the type $\Sigma \sim r^{-3/2}$. Disk models have masses between 0.075 and $0.125M_{\odot}$ and initial temperature profiles as those used in MA02. The minimum temperatures are reached at the outer edge of the disk and range from 36 to 60 K. More details on the setup of the initial conditions are explained in MA03.

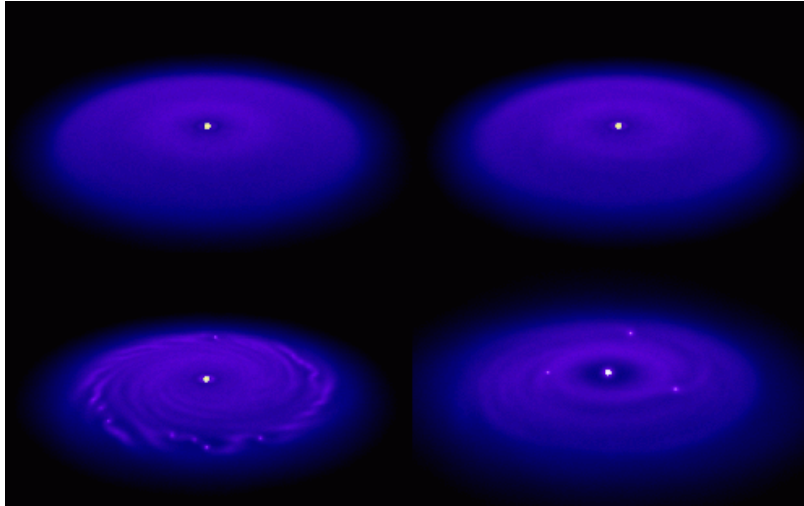


Figure 1. Snapshots of the simulation in which the disk is grown in mass (see text, section 2.1). The disk logarithmic density is shown using color-coding and for an inclination of 45 degrees with respect to the disk plane; brighter colors are used for higher densities, and maximum densities are of order 10^{-6} g/cm³. From top left to bottom right, boxes show the inner 25 AU at $t=0$, $t=300$ years, $t=450$ years and $t=650$ years.

Models are evolved with a locally isothermal or with an adiabatic equation of state; the new runs adopt an adiabatic equation of state with the addition of radiative cooling and heating. In all cases we include a standard Monaghan artificial viscosity to model shocks, with typical values of the coefficients $\alpha = 1$ and $\beta = 2$. The artificial viscosity term appears in both the momentum and the energy equation, hence irreversible shock heating is included, except in the locally isothermal equation of state, where by construction the thermal energy of any given particle is assumed to be constant.

Radiative cooling is implemented using a prescription similar to that used by Rice et al. (2003a) (see also Pickett et al. 2003); the cooling timescale is simply assumed to be proportional to the local orbital frequency of particles, $t_{cool}(r) = A\Omega(r)^{-1}$. In addition we introduce a density dependent criterion, so that when a region grows beyond a specified threshold, radiative cooling is completely switched off. In the runs presented here the density threshold is fixed at 5×10^{-10} g/cm³ — this is a conservative choice based on the recent calculations by Boss (2001) with radiative transfer, which show that at such densities the temperature evolves in a nearly adiabatic fashion. In runs that are evolved using a locally isothermal equation of state we simply switch to an adiabatic equation of state throughout the disk once such density threshold is reached somewhere (see also MA02).

In the runs with radiative cooling we heat the inner part of the disk by means of another radially dependent term (this goes exponentially to zero at $R = 10$ AU) so that a gravitationally stable disk ($Q > 2$) develops a temperature profile

similar to that used in the initial conditions of the locally isothermal runs (the latter was indeed motivated by the results of the radiative transfer models of Boss (1996) that include irradiation from the central star and compressional heating due to material infalling onto the disk from the molecular cloud, see MA03).

The simulations are run with GASOLINE, a parallel tree-based gravity code with SPH hydrodynamics which uses multistepping to evolve efficiently a wide density range (Wadsley, Stadel & Quinn 2003).

2. Results

In what follows we describe the main results of our large suite of numerical simulations, describing first the locally isothermal and purely adiabatic runs, and then those including radiative cooling and heating. A detailed description of the former can be found in MA03.

2.1. Locally isothermal and adiabatic runs

Disks evolved with a locally isothermal equation of state and with $Q_{min} < 1.4$ fragment after 6-7 orbital times (we used the orbital time at 10 AU, 28 years, as a reference), the others ($Q_{min} = 1.5 - 1.9$) develop only from very strong to moderate spiral patterns which reach a peak amplitude after 6-7 orbital times and then fade and saturate towards a nearly stationary pattern (see MA02). With $Q_{min} < 1.4$, clump formation proceeds even when the equation of state is switched from locally isothermal to adiabatic once the critical density threshold is reached (see previous section), although the clumps that survive and become gravitationally bound are fewer due to strong shock heating along the spiral arms (see MA03). Clumps form on eccentric orbits (these follow the path of the spiral arms) at scales from below to just about one Jupiter mass, for disks with masses in the range $0.075 - 0.1M_{\odot}$. For the same value of Q_{min} , lighter and colder disks produce clumps with appreciably smaller mass; the minimum scale of fragmentation is indeed set by the local Jeans mass, and it can be shown that this scales as $T^{5/4}$ for a fixed value of Q_{min} (see MA03). The higher the mass resolution (higher number of particles) the higher is the number of gravitationally bound condensations that arise. On the other end, $Q_{min} \sim 1.4$ marks the threshold between fragmenting and non-fragmenting disks in a way that is independent on resolution; disks with $Q_{min} = 1.5$ or higher were evolved with increasing number of particles, always formed strong spiral patterns but these never broke up into clumps. The degree of fragmentation depends very weakly on the magnitude of the coefficients of artificial viscosity; there is a trend of stronger fragmentation with lower viscosity but once again this does not affect the threshold Q_{min} (see MA02).

We investigate how the outcome of our simulations depends on the way we set up the initial conditions by running a test in which an initially very light disk ($M = 0.0085M_{\odot}$) is grown in mass at a constant rate over tens of orbital times until it reaches the same (ten times bigger) mass of one of our standard disk models undergoing clump formation (the temperature is kept fixed and is equivalent to that used for the latter model). Fragmentation occurs even in such growing disk once the outer regions approach $Q_{min} = 1.4$ (Figure 1); this shows

that weaker non-axisymmetric torques occurring at higher values of Q while the disk grows do not lead to self-regulation of the disk at values of Q higher than 1.4 through mass redistribution. The results of this experiment weaken considerably one of the arguments against gravitational instability, namely that in real disks spiral instabilities would always saturate before fragmentation becomes possible (Laughlin & Rozyczka, 1996). A few simulations with 200,000 particles were carried out for as many as 30 orbital times to probe the evolution of the system of protoplanets up to about 1000 years. Several mergers occur over a few orbital times after the fragmentation has started, leaving 2 or 3 protoplanets with masses between 0.7 and $6M_J$ on orbits with eccentricities in the range $e = 0.1 - 0.3$. The surviving protoplanets continue to accrete mass at a rate which is strongly dependent on the equation of state adopted in this later part of the evolution. For adiabatic conditions the accretion is negligible and the values we just quoted should well represent the final masses of the planets, whereas for isothermal conditions the accretion rate can be as high as $10^{-5}M_\odot/\text{yr}$, and so protoplanets can reach brown dwarf-like masses in a few thousand years (the latter is the estimated lifetime of the disk before it is accreted onto the central star due to the strong gravitational torques, see MA03).

We also performed a number of runs in which disks are evolved with an adiabatic equation of state since the very beginning. We explore different initial Q_{min} and different values of γ , in the range $1.2 - 1.4$. We find fragmentation only in runs starting from a very massive disk ($M = 0.125M_\odot$) with unrealistically low values of Q , $Q < 0.9$, and only for $\gamma = 1.3$ or lower. In particular only if $\gamma = 1.2$ do clumps survive for several orbital times and become gravitationally bound. At these low values of Q mass redistribution and shock heating are indeed so efficient that the disk quickly departs from the initial conditions; such configurations are therefore unrealistic.

3. Runs with radiative cooling and heating

In these runs (10^6 particles) fragmentation is obtained for sufficiently short cooling timescales (Figure 2). For any given initial disk model we first run a simulation with a long cooling timescale which is expected to yield a stable configuration (see Rice et al. 2003a) and then we re-simulate the same disk with increasingly smaller cooling timescales until we enter a regime where fragmentation takes place. We find that the latter occurs for critical cooling timescales in the range $0.3 - 1.5T_{orb}$ depending on disk mass (this varies between 0.085 and $0.1M_\odot$) and on the value of γ used in the equation of state. At larger masses the higher disk self-gravity can amplify non-axisymmetric perturbations more effectively and more rapidly, so lower cooling rates are needed to counteract heating from strong compressions and shocks along the spiral arms. For values of $\gamma = 5/3$ our results are in very nice agreement with those of Rice et al. (2003a,b), who used lower resolution SPH simulations and a different setup of the initial conditions; we both find that $T_{cool} \sim 0.8T_{orb}$ or smaller is necessary to trigger fragmentation in a disk with a mass $M = 0.1M_\odot$ (see Figure 2). Instead, the critical cooling timescale for the same disk rises by more than 50% if $\gamma = 7/5$ like in Boss (2002), supporting his claim that convective transport of

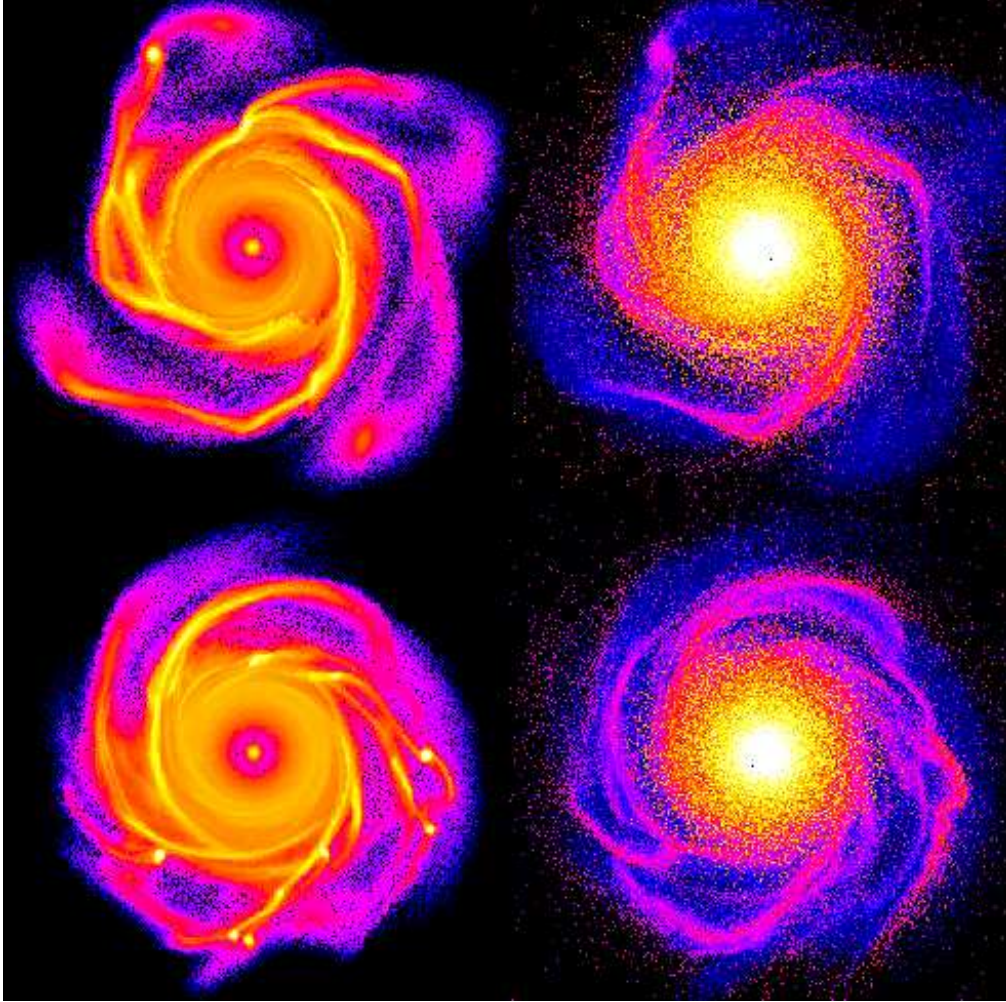


Figure 2. Disk simulations with cooling and heating. Logarithmic density (left) and linear temperature maps (right) are shown for two simulations employing 10^6 gas particles in the disk, after 300 years of evolution. On top, the disk has a mass $M = 0.1M_{\odot}$, and we used $\gamma = 5/3$ and $A = 5$ (see section 2 and 3). At the bottom, the disk has a mass $M = 0.085M_{\odot}$, and we used $\gamma = 7/5$ and $A = 3$. Brighter colors correspond to higher values of the variables plotted. Note the heating due to shocks along the spiral arms and the higher temperatures at the location of the protoplanets (up to 300 K). Boxes are 25 AU on a side.

energy at a rate comparable to the orbital time is enough to sustain the instability. Like in the runs described in the previous section, overdense regions grow rapidly in mass and reach fragmentation provided that Q_{min} drops below 1.4. When comparing the same disk models, while most features like the type of spiral pattern and the number of clumps formed are comparable in these radiative runs and in those started with a locally isothermal equation of state, the spiral arms appears thinner and more filamentary in these new runs, owing to sharper density and pressure gradients. The different density profile across the spiral arms is probably due to the fact that shock heating begins as soon as the first non-axisymmetric structure appears in the new runs, whereas it is completely inhibited below the critical density threshold in the locally isothermal runs.

We note that disks that undergo fragmentation in the simulations of Rice et al. (2003a,b) do that in a much stronger fashion compared to ours, with several tens of gravitationally bound clumps instead of the few (between 1 and 10, see Figure 2) that survive the first violent phase of the gravitational instability in our runs. This difference certainly arises because we shut off cooling in the overdense regions once they grow beyond the density threshold, while Rice et al. do not. In our runs the sites of formation of the protoplanets coincide with those of the strongest pressure and temperature gradients along the spiral arms (see Figure 2), thus it is not surprising that only the highest overdensity peaks survive (see also Pickett et al. 2003); later, while the instability starts to fade away, these few gravitationally bound clumps will be able to survive for long timescales quite irrespective of the thermodynamical scheme adopted because the disk enters a more quiet phase of its evolution and strong compressions do not occur anymore (see MA03). However, even during the subsequent evolution we expect that allowing or not allowing cooling within the densest regions will make a difference; clumps would contract nearly isothermally if strong cooling is always active and will reach higher mass concentrations and thereby smaller effective sizes compared to the case in which cooling has been inhibited (see also Figure 2 of MA03 that compares two runs with a locally isothermal equation of state, one with and one without the switch to adiabatic later in the evolution). A different size implies a different cross section for mergers, and therefore a different mass spectrum and number of the clumps after many orbital times.

Mass accretion rates of protoplanets are quite close to those found in previous runs in which the disk was evolved adiabatically after fragmentation (see MA03). One simulation with 10^6 particles was carried out for 600 years (equivalent to more than 20 orbital times at 10 AU); in that we measured accretion rates $< 10^{-6} M_{\odot}/\text{yr}$ during the late stage, although there is considerable scatter when we look at the individual “histories” of the protoplanets — protoplanets that venture inside 10 AU are heated considerably and they can even lose some mass at the pericenter of their orbit, whereas those that spend most of the time at $R > 10$ AU have the highest accretion rate since they easily sweep the cold gas along their trail.

4. Conclusions

Gravitational instability continues to remain a very attractive mechanism to explain the origin of gas giants, especially those found in extrasolar planetary

systems. With our new runs we showed that the mass range of bound condensations arising along the spiral arms is significantly broad once the relevant disk parameters are changed; the outcome is not necessarily “SuperJupiters”, protoplanets even as small as Saturn can be formed. The general picture is confirmed with runs that directly model radiative heating and cooling; the only necessary requirement for the instability to proceed is that the cooling time must be comparable or only slightly larger than the orbital time at some point of disk evolution. Once protoplanets are formed, mergers during the first few orbital times and accretion of disk gas over longer timescales are the two ways by which they can grow in mass. How much they can grow will depend a lot on the details of heating and cooling. Our results suggest that, even if the cooling time remains comparable to the orbital time in the outer disk, a mass of $\sim 10M_J$ might be an upper limit if gravitational torques cause the dissipation of most of the disk on timescales of about 10^4 years (see also MA03).

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